



Ranking the ecological effects of coastal armoring on mobile macroinvertebrates across intertidal zones on sandy beaches

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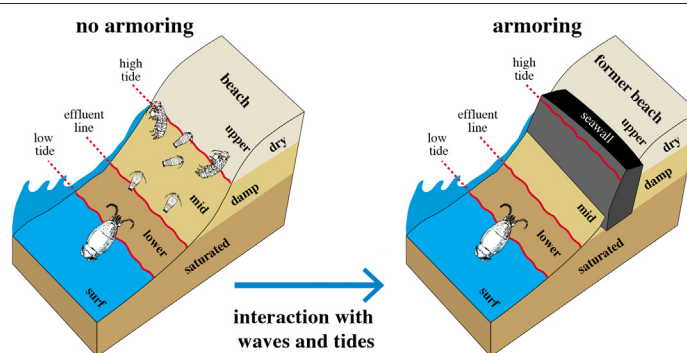
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HIGHLIGHTS

- Coastal armoring is a common societal response to shoreline erosion around the world
- Armoring placed on sandy beaches can affect multiple ecosystem features and functions.
- Evaluated effects of coastal armoring on mobile macroinvertebrates across intertidal zones on beaches of Chile and California
- Armoring effects on fauna increased from the low to the upper intertidal zones
- The number of intertidal zones affected by armoring depended on its location on the beach profile, armoring located lower on the profile affected a greater number of intertidal zones

GRAPHICAL ABSTRACT



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ABSTRACT

Coastal armoring is widely applied to coastal ecosystems, such as sandy beaches, in response to shoreline erosion and threats to infrastructure. Use of armoring is expected to increase due to coastal population growth and effects of climate change. An increased understanding of armoring effects on those ecosystems and the services they provide is needed for impact assessments and the design of these structures. We investigated the following hypotheses: 1) impacts of coastal armoring on beach macroinvertebrates increase from lower to upper intertidal zones and 2) location of an armoring structure on beach profiles affects the number of intertidal zones, using comparative surveys of armored and unarmored beach sections in Chile and California. The effects of armoring were greater for upper intertidal (talitrid amphipods) and mid-intertidal species (cirranid isopods) than for lower shore fauna (hippid crabs). Our surveys of sections of armoring structures located higher and lower on the beach profile (with and without interactions with waves and tides), showed loss of upper zone talitrid amphipods and mid-zone isopods and a reduction of lower zone hippid crabs in sections where the structures were lower on the beach profile and interacted with waves, compared to non-interacting sections. Our results support the hypothesis that impacts of armoring on intertidal macroinvertebrates increase from the lower to the upper intertidal zones of sandy beaches and also suggest that the relative position of an armoring structure on the beach profile, determines the number of intertidal zones it affects. Our findings also imply that by altering the position of existing

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armoring structures on the shore profile and increasing the amount of interaction with waves and tides, sea level rise and regional factors, such as coseismic coastal subsidence, can be expected to exacerbate the impacts of these widely used coastal defense structures on sandy beach ecosystems.

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1. Introduction

Shoreline armoring and other engineered coastal defenses are common societal responses to threats from coastal erosion and shoreline retreat (see reviews by Nordstrom, 2014; Charlier et al., 2005). Coastal armoring is placed on all types of sedimentary shores, including exposed sandy beaches and sheltered habitats such as salt marshes, tidal flats and estuarine bottoms (e.g., Dethier et al., 2016; Dugan et al., 2017; Gittman et al., 2015; Nordstrom, 2014; Sobocinski et al., 2010; Toft et al., 2013). By fixing shoreline position, coastal armoring structures constrain the possible responses and evolution of shorelines to changes in sea level and other dynamic coastal processes. The ecological effects of shoreline armoring are receiving increased recognition and attention including a meta-analysis by Gittman et al. (2016) and field studies by Lee et al. (2018) and others, however the majority of studies are conducted in sheltered environments, such as marshes and estuaries, with far less work on exposed open coast ecosystems, such as sandy beaches (Dugan et al., 2017). Despite widespread use of armoring structures on open coasts, the general lack of information about the ecological effects of shoreline armoring represents a critical gap in the knowledge needed to sustain these coastal ecosystems and the functions that they provide.

Sandy beach ecosystems are highly valued as economic and cultural assets for society (King and Symes, 2004; Pendleton and Kildow, 2006). They harbor unique biodiversity (McLachlan and Defeo, 2017) and provide a wealth of ecosystem functions, including storm protection, nutrient cycling, water filtration, detrital processing, and wildlife support (Defeo et al., 2009). Rapidly growing human populations and expanding development are intensifying pressures on these valuable coastal ecosystems. Sea-level rise and other predicted effects of climate change are expected to exert even greater pressures on these ecosystems at the edge of land and sea, exacerbating erosion, degrading habitat, and accelerating shoreline retreat (Airolidi et al., 2005; Vitousek et al., 2017; Myers et al., 2019).

A variety of ecological effects of coastal armoring for open coast sandy beaches have been shown to date including impacts to availability of macroalgal wrack and the abundances of talitrid amphipods (Dugan and Hubbard, 2006; Dugan et al., 2008, 2013), cirrolanid isopods and hippid crabs (Jaramillo et al., 2002), ocapodid crabs (Lucrezi et al., 2010) and shorebirds (Dugan et al., 2008). However, hypotheses concerning the relative ecological effects of coastal armoring across the major intertidal faunal zones of sandy beaches have never been thoroughly evaluated. This information will be valuable in projecting ecological impacts of new and existing armoring structures on sandy beach ecosystems and the services they provide.

The mobile macroinvertebrates of sandy beaches around the world are commonly distributed in three dynamic intertidal zones (e.g. Dahl, 1952; Trevallion et al., 1970; McLachlan and Jaramillo, 1995; McLachlan and Defeo, 2017). The upper zone is centered around the drift line and extends above that; the mid zone extends from below the drift line down to the effluent line or water table outcrop, while the lower zone extends from the effluent line into the surf zone. These zones generally correspond to the relative dry upper intertidal zone located at and above the drift line, a damp mid intertidal zone or retention zone and the saturated lower intertidal or resurgence zone (cf., Salvat, 1964). The main faunal components of the upper, mid and lower

zones are talitrid amphipods, cirrolanid isopods and hippid crabs (Dahl, 1952; Trevallion et al., 1970; McLachlan and Jaramillo, 1995; McLachlan and Defeo, 2017).

The dynamic intertidal zones of exposed sandy beaches have been shown to respond to coastal armoring (e.g., Dugan and Hubbard, 2006; Dugan et al., 2008; Jaramillo et al., 2012). As beaches lose width in response to armoring, intertidal zones lose habitats disproportionately, proceeding from the upper intertidal zones to the lower beach (Dugan et al., 2008). When the upper beach and drift line habitat shift from the sandy substrate of the beach to the armoring structure, the three-dimensional dense macroinfaunal beds characteristic of this zone are replaced by the steep, reflective, two-dimensional habitat of the armoring.

Regarding physical impacts of armoring, the lower an armoring structure is located with respect to high water levels, the greater the physical impacts associated with the structure are expected to be (Weggel, 1988; Weigel, 2002a, 2002b, 2002c). It could be expected that ecological impacts of armoring would follow a similar pattern. It has been also argued that variation in losses of sandy beach habitat along armored coasts arises from variability in elevations of seawalls or revetments relative to sea level (Ruggiero, 2010). Conceptually, as the intertidal elevation of an armoring structure declines it experiences greater hydrodynamic energy with the expected consequence of magnifying the influence the structure exerts on a given coastal ecosystem and the expected ecological effects (Dugan et al., 2017).

Exposed sandy beaches of south-central Chile and California harbor a similar highly mobile crustacean fauna with talitrid amphipods in the upper intertidal zones, cirrolanid isopods in the mid zones and hippid crabs in the lower intertidal zones (Dugan et al., 2003, 2013; Jaramillo, 1987; Jaramillo et al., 1993; McLachlan and Jaramillo, 1995). Using closely related taxa of upper and lower intertidal zones of beaches in Chile and California, we evaluated two conceptual hypotheses on the ecological impacts of coastal armoring on mobile intertidal macroinvertebrates. First, we compared responses of upper and lower shore taxa to investigate the hypothesis that ecological impacts of armoring increase from the lower to the upper intertidal zones (Fig. 1). We had the opportunity to include comparisons of mid intertidal cirrolanid isopods to test this hypothesis, since two sympatric species with distinct intertidal zonation (e.g. Jaramillo and Fuentealba, 1993) are common inhabitants along sandy beaches of south-central Chile. Second, we evaluated the hypothesis that the number of faunal zones affected by an armoring structure increases with decreasing elevation of the structure on the beach profile (Fig. 2).

2. Material and methods

2.1. The study regions and sites

In south central Chile the 9 beaches studied spanned ~150 km of north – south coastline, while in California the 5 study beaches were distributed along ~75 km of an east – west trending coast (Fig. 3; Table S1 for geographic locations). In both regions, we compared sections of beaches backed by seawalls or rock revetments with unarmored sections located at the same beaches (see Fig. 4 as example). Those two types of armoring structures were the most common on both study coastlines. Our comparisons used one treatment for beaches in both regions: armored sections, including shores lined with seawalls or rock revetments. Adjacent to each treatment site, unarmored sections with

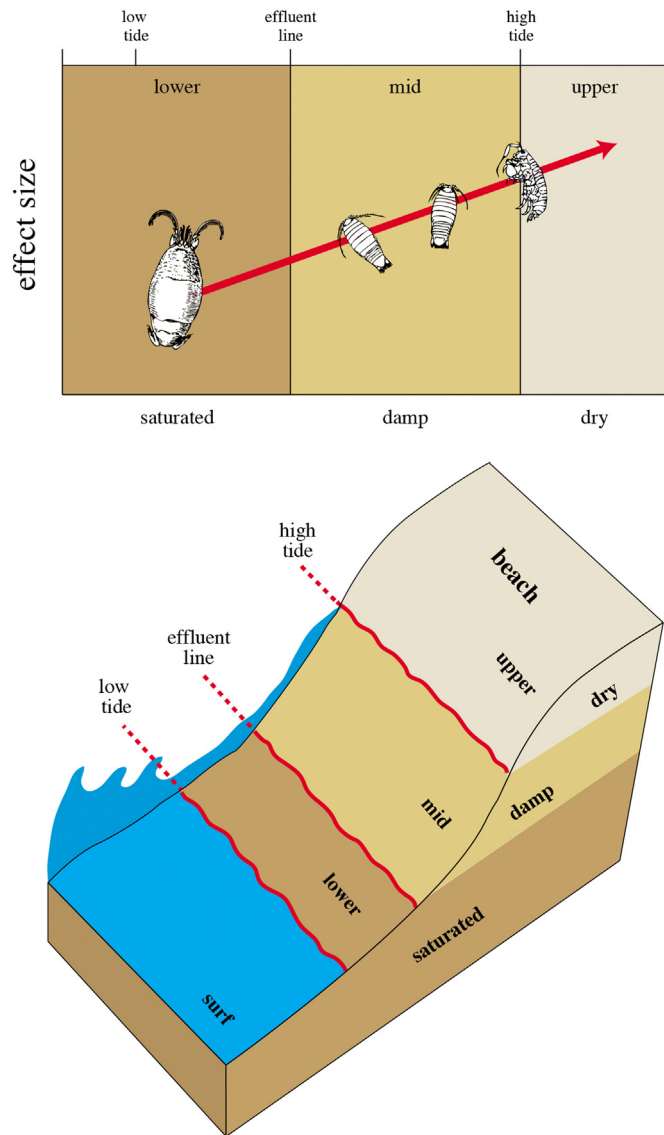


Fig. 1. Schematic representation of hypothesized ranking of the effects of coastal armoring on mobile sandy beach macroinvertebrates from the lower to the upper beach zones. Anomuran decapods, cirrolanid isopods and talitrid amphipods are the most typical macroinvertebrates at the lower saturated, mid damp and upper dry beach zones, respectively. The upper dry zone is the beach zone at, above and just below the 24 h high tide mark, the mid damp zone is the intertidal from below the high tide line to the effluent line, and the lower saturated zone is the beach zone below the effluent line extending into the swash and surf zones.

undeveloped shores that lacked any manmade armoring structures were used as controls. During the respective summer sampling periods in Chile (January & February 2010) and California (July 2009), we also surveyed a series of study sites on the same stretches of beach where the degree to which armoring structures interacted with waves during high tides (i.e., waves hit the armoring structure during high tides removing sand from the upper levels of the beach), varied along a gradient from fully interacting to not interacting. All our surveys were conducted during spring low tides when all the seawall and rock revetment sections and the unarmored sections had sandy intertidal habitat available.

2.2. Fauna

The dominant intertidal macroinvertebrates of the sandy beaches of south-central Chile and southern California are very similar. The upper shore zone is primarily occupied by talitrid amphipods (*Orchestoidea*

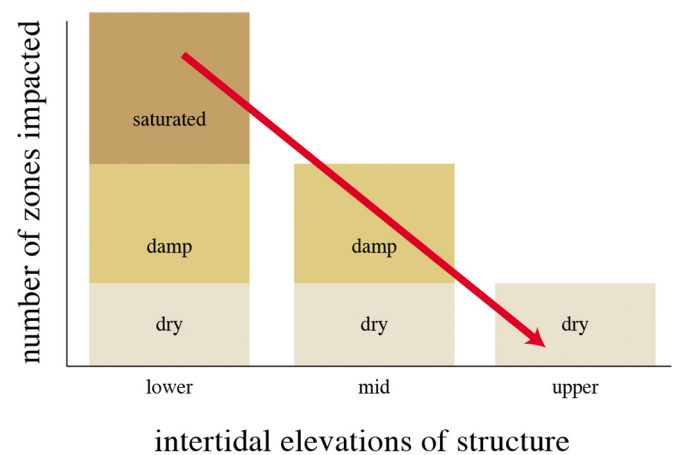


Fig. 2. Schematic representation of the hypothesized effects of the position of an armoring structure on the intertidal beach profile on the number of intertidal zones and biota. As position of structure shifts down the intertidal profile towards the lower saturated beach zone, the number of impacted intertidal zones and biota increases.

tuberculata Nicolet in Chile and *Megalorchestia* spp. in California) and is usually centered on the drift line or high tide level (Dugan et al., 2013; Jaramillo, 1987; McLachlan and Jaramillo, 1995). The lower shore zone of both study areas is occupied primarily by the hippid crab *Emerita analoga* (Stimpson) whose distribution extends from the effluent line to the lowest tide level (McLachlan and Jaramillo, 1995). In Chile we also sampled the mid shore zone which is occupied by two cirrolanid isopods, *Excirrolana braziliensis* Richardson and *Excirrolana hirsuticauda* Menzies. The across shore distribution of *E. braziliensis* is centered around the drift line, while that of *E. hirsuticauda* extends from below that level to the effluent line of the beach (Jaramillo and Fuentealba, 1993).

2.3. Collection of samples

We collected samples of intertidal macroinvertebrates (i.e., invertebrates retained on a 1 mm sieve) at beach sections with and without coastal armoring along both coasts, during spring low tides. Samples were collected along four replicated shore normal transects spaced 5 m apart from each other. Each transect extended from the upper intertidal to the low tide level of the beach when possible. Our sampling focused on the typical dominant taxa of each intertidal zone and we surveyed the upper and lower shore faunal zones on both coasts. Five 10 cm diameter cores of sand were collected to a depth of 20 cm at equally spaced levels across each of the faunal zones of the four transects, totalling 0.04 m² surface area per intertidal zone on each transect. The five cores from each zone of a transect were pooled and sieved through a 1 mm sieve. The retained organisms were stored in 10% formalin in sea water until sorting and identification in the laboratory.

2.4. Data analyses

We carried out two types of analyses to evaluate our hypotheses. The first one used paired comparisons of data on intertidal macroinvertebrates from sections located in front of interacting armoring structures (either seawalls or rock revetments) and from adjacent unarmored sections in Chile and California (the between site comparisons, point i below). The second analysis compared variation in macroinvertebrates across alongshore gradients in armoring position (the within site comparisons, point ii below).

i) To evaluate the responses of the macroinvertebrates of different intertidal zones to armoring, the abundances of talitrid amphipods

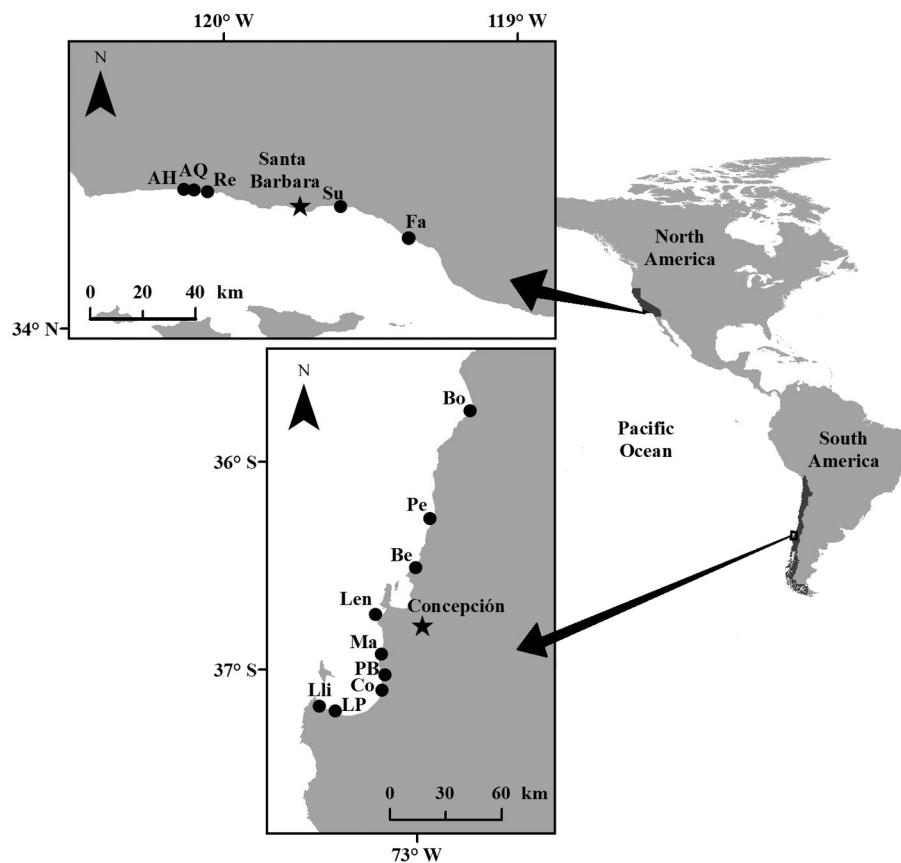


Fig. 3. Locations of the study beaches along the coasts of south-central Chile and southern California. For Chilean beaches the site codes are: Lli = Llico, LP = Las Peñas, Co = Colcura, PB = Playa Blanca, Ma = Maule, Len = Lenga, Be = Bellavista, Pe = Peyuhue and Bo = Boyeruca. For Californian beaches the site codes are: AH = Arroyo Hondo, AQ = Arroyo Quemado, Re = Refugio, Su = Summerland and Fa = Faria.

and hippid crabs collected at Chilean and Californian beaches which had paired contrasting situations in relation to coastal armoring (i.e., armored and unarmored sections) - independent from the coast studied - were analysed as follows: data collected from sections located in front of seawalls and rock revetments were pooled and contrasted against data collected from unarmored sections (Table S2). Abundances of cirrolanid isopods from Chile were treated as above; i.e., pooled data from sections in front of interacting seawalls and rock revetments were contrasted against data collected from adjacent unarmored sections of coast (Table S3). We used Kruskal-Wallis non-parametric statistical test (H statistic) to evaluate the responses of the macroinvertebrates of different intertidal zones to armoring. We estimated the effect size or magnitude of the differences between groups of data by using Cohen's d Index or epsilon squared (see Sullivan and Feinn, 2012) for all three taxa.

ii) To compare abundances of macroinvertebrates along a gradient of interacting and non-interacting sections of the same armoring structures, the abundances of talitrid amphipods and hippid crabs from Chile and California and cirrolanid isopods from Chile collected at sites that differed in elevation/position relative to sea level (i.e., sites with and without interactions with waves and tides during sampling times) (Table S4), were analysed as explained above (point i). These within site comparison analysis also included the collection of upper and lower intertidal macroinvertebrates along the length of a seawall and a rock revetment in Faria, California (Fig. 5), representing a gradient of structure elevations, ranging from low on the profile where interaction with waves and tides was nearly continuous to high on the profile where interactions with waves and tides did not occur during sampling times (Table S5). We also used Kruskal-Wallis non-parametric statistical test (H statistic) and

estimated the effect size or magnitude (see Sullivan and Feinn, 2012) to compare abundances of macroinvertebrates at the interacting and non-interacting sections of the armored structures studied at Chile and California. We also used linear regression for abundance data of talitrid amphipods and *Emerita analoga* against distance along the seawall and rock revetments of Faria.

3. Results

3.1. Between beach comparisons

Overall, the greatest effects of armoring were observed for abundance of species of the upper intertidal zone and relative effects increased from the low to the upper intertidal zone as predicted by our first hypothesis (Figs. 1, 6). Abundances of talitrid amphipods were significantly lower ($p < 0.05$) at sections located in front of seawalls and revetments, compared with adjacent unarmored sections ($H = 11.3$ and 5.4 and effect size = 67% and 77% for Chile and California, respectively) (Fig. 6). In the mid intertidal zone significant effects ($p < 0.05$) of armoring on abundance were observed for one species of cirrolanid isopod in Chile (*E. braziliensis*; $H = 5.7$, effect size = 33%) that lives close to the top of that zone with a lower effect size than found for upper zone talitrid amphipods. The responses of species inhabiting the lower intertidal zones to armoring were not statistically significant ($p > 0.05$) and effect sizes were lower (Fig. 6). This group of taxa included the other species of mid intertidal isopod in Chile (*E. hirsuticauda*; $H = 0.0$, effect size = 0) and the low intertidal hippid crab *E. analoga* ($H = 3.5$ and 2.1 and effect size = 20 and 30% for Chile and California, respectively) (Fig. 6).

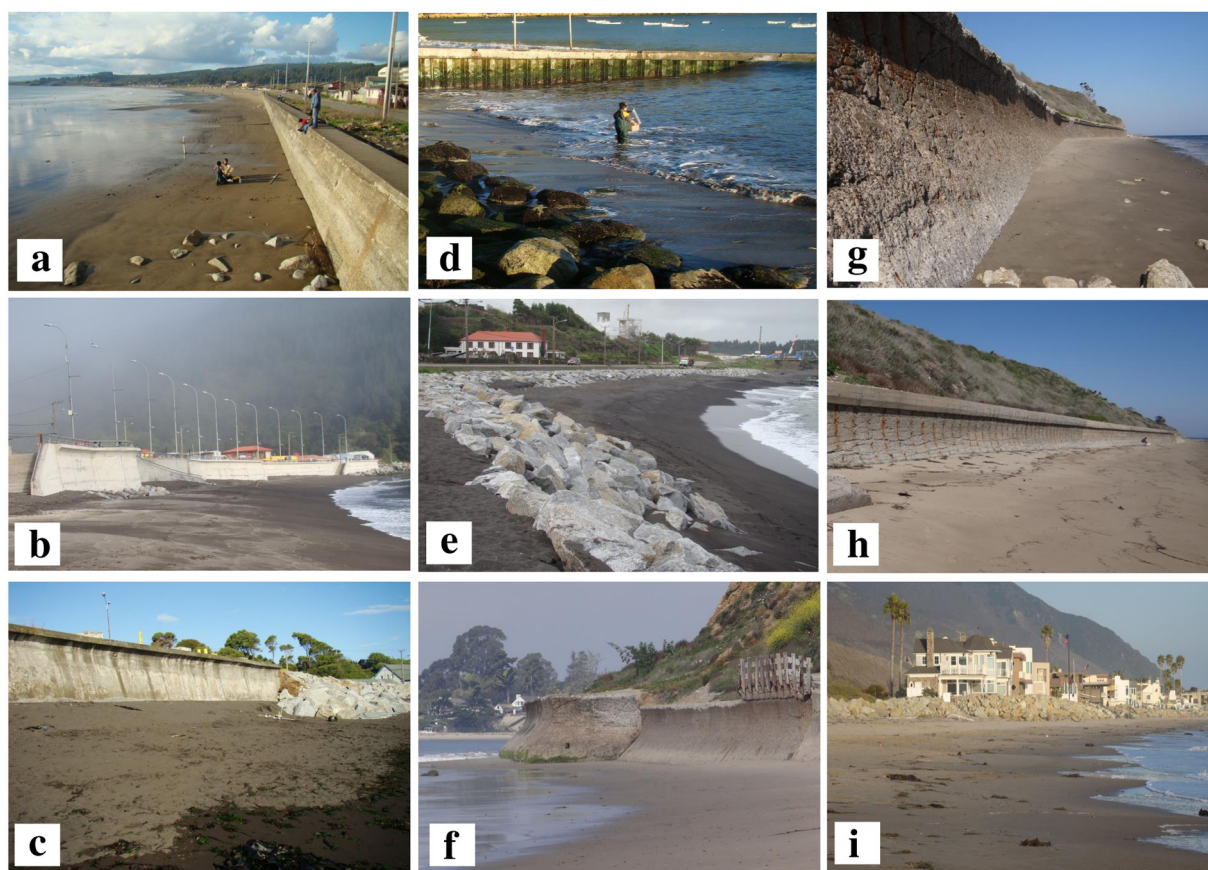


Fig. 4. Representative images of the coastal armoring structures used in comparisons of the study beaches. South-central Chile: the seawalls at Playa Blanca, Lenga and Maule (a, b and c, respectively) and rock revetments at Lico and Maule (d and e, respectively). California: seawalls at Summerland, Refugio and Arroyo Quemado (f, g and h, respectively) and a rock revetment at Faria (i).

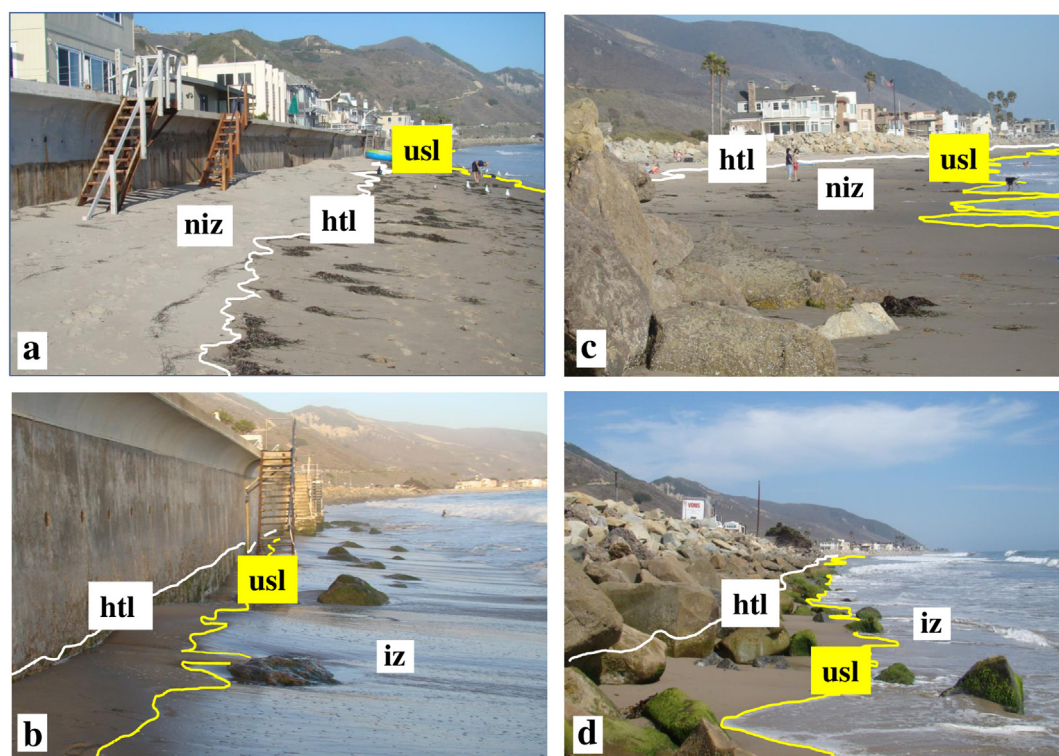


Fig. 5. Images from the armored sandy beach at Faria (California). a) The non-interacting zone in front of the seawall, b) the interacting zone in front of the seawall, c) the non-interacting zone in front of the rock revetment, and d) the interacting zone in front of the rock revetment. Htl = high tide level, usl = upper swash level, niz = non-interacting zone, iz = interacting zone.

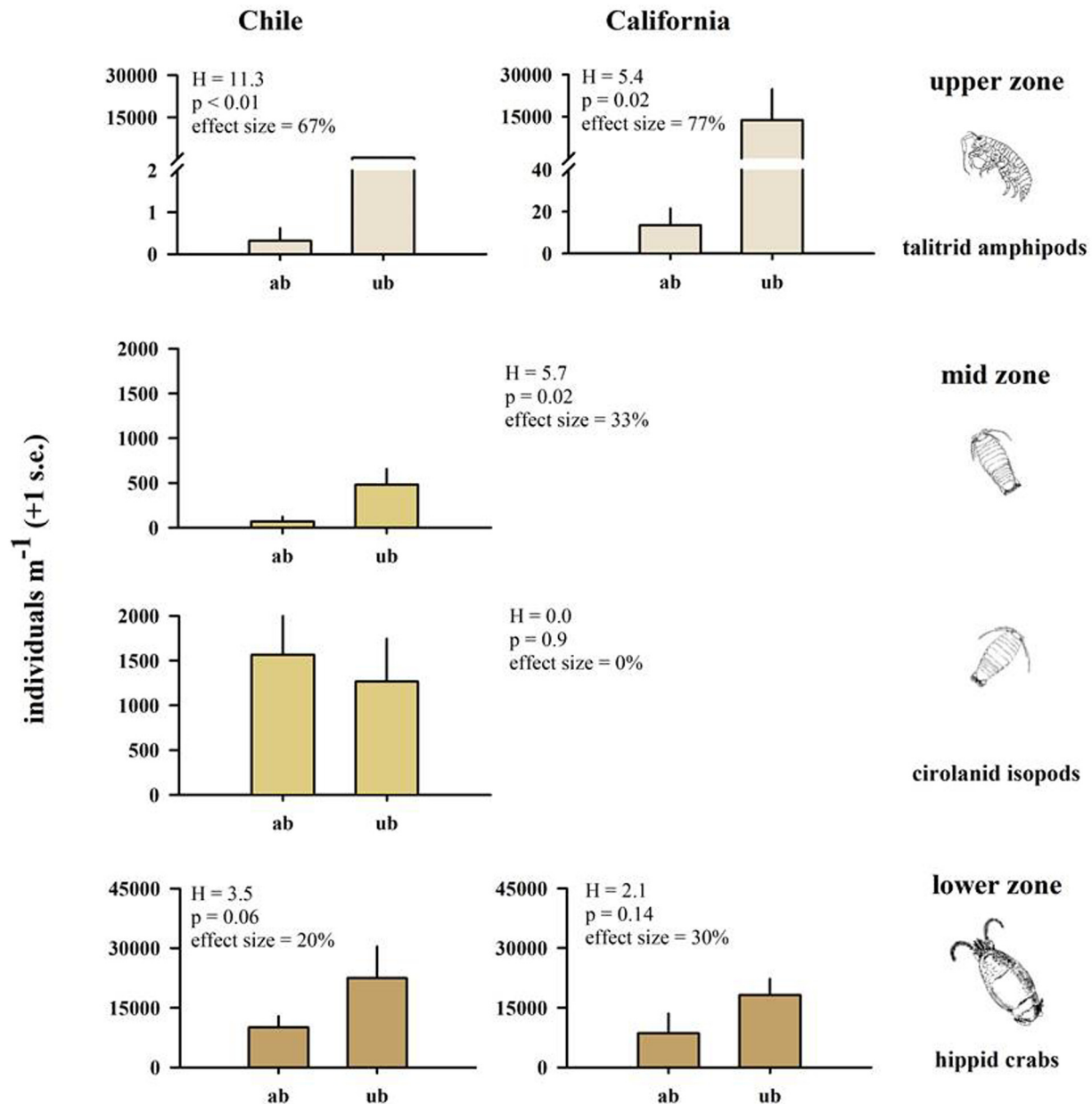


Fig. 6. Mean values (+ 1 standard error) of abundance of intertidal invertebrates: talitrid amphipods (*O. tuberculata* and *Megalorchestia* spp. in Chile and California, respectively), cirolanid isopods (*E. braziliensis* and *E. hirsuticauda* (upper and lower drawings, respectively) in Chile) and hippid crabs (*E. analoga* at both coasts) in armored and unarmored beach sections (ab and ub, respectively) of south-central Chile and California (between site comparisons).

3.2. Within beach comparisons

The effects of armoring on fauna were stronger for structures located lower on the beach profile where waves and tides interacted with the structures even during low tide and wave condition, as predicted in our second hypothesis (Figs. 2, 7). In comparisons carried out along an interacting rock revetment in south-central Chile (Bellavista) and an interacting seawall in California (Arroyo Hondo), the typical intertidal species of the upper and the mid zones were absent from sections where the armoring structure was washed by waves and tides during the sampling time (Fig. 7). On the other hand, abundance of the low intertidal species, *E. analoga*, at those sites was not consistently affected by the armoring in our comparisons (Fig. 7). While no significant differences ($p > 0.05$) were evident at Bellavista ($H = 0.3$, effect size = 11), the abundances of *E. analoga* was significantly lower ($p < 0.05$) at the interacting section of the seawall studied at Arroyo Hondo ($H = 5.3$, effect size = 76) (Fig. 7). The strong differences in wave climate between

the study beaches in Chile and California during our surveys provide insights on these results (Fig. 7). On the beach in California where waves were larger during our survey, the effect of armoring was significant even on this robust lower beach species. On the beach in Chile where waves were small during our survey, no significant effect of armoring on *E. analoga* was found.

For the upper intertidal zone animals (talitrid amphipods), our results along an armored shoreline at Faria (California), show these animals were absent at all sampling points where the armoring structures were interacting with waves and tides, both in front of a seawall and a rock revetment (Fig. 8). Using distance from the armoring structure to the high tide level or drift line as a proxy for suitable habitat availability for those organisms, a significant alongshore trend ($p < 0.05$) in the log $n + 1$ transformed abundance of talitrid amphipods was evident ($r^2 = 0.690$ seawall, $r^2 = 0.476$, rock revetment) (Fig. 8). For swash zone dwelling hippid crabs, *Emerita analoga*, the responses of abundance to interaction with armoring differed between the seawall

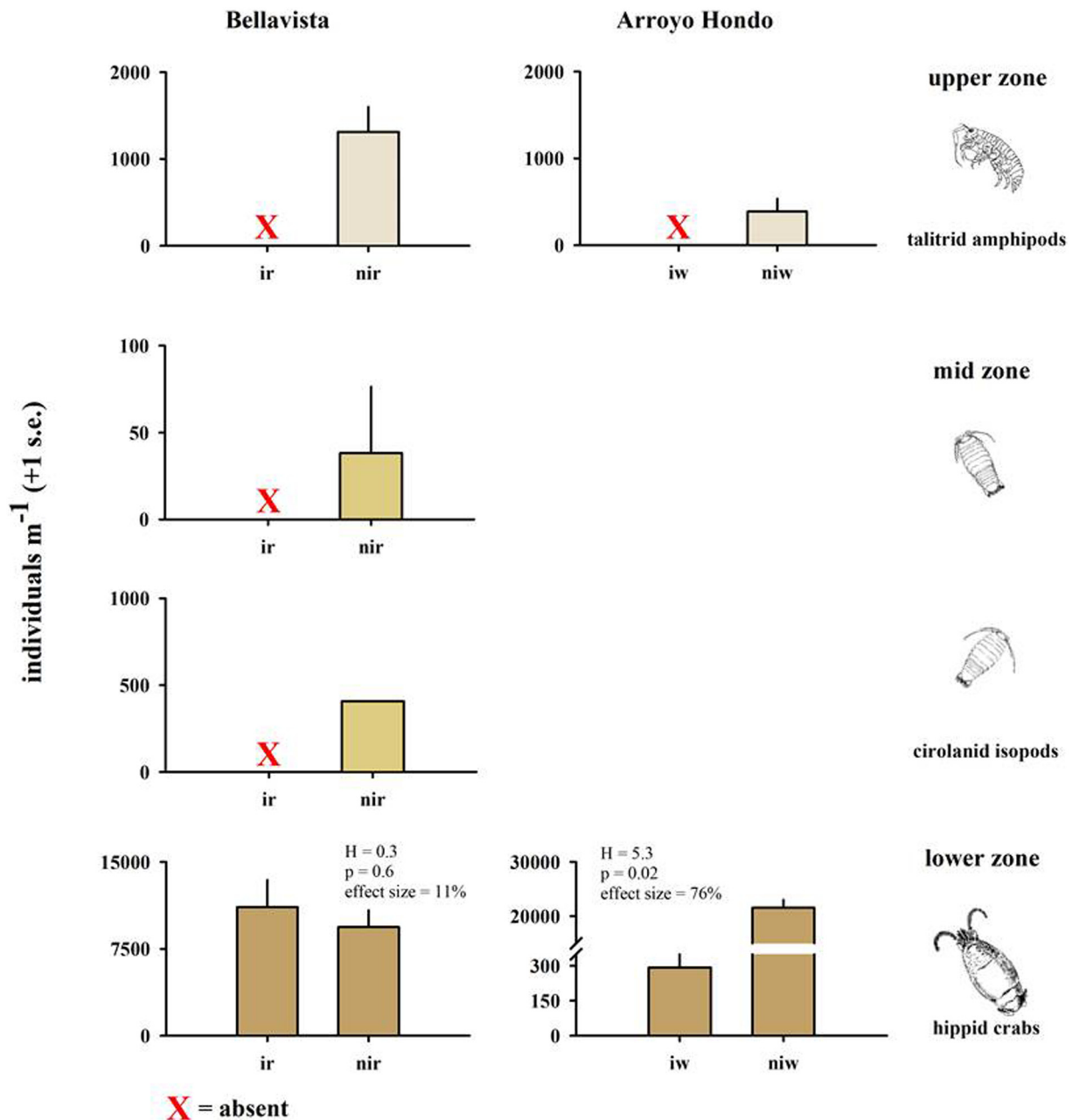


Fig. 7. Mean values (± 1 standard error) of abundance of talitrid amphipods (*O. tuberculata* and *Megalorchestia* spp. in Chile and California, respectively), cirolanid isopods (*E. braziliensis* and *E. hirsuticauda* (upper and lower drawings, respectively) in Chile and hippid crabs (*E. analoga* at both coasts) in interacting and non-interacting sampling areas where the same coastal armoring structure was located at different elevations in relation to relative sea level at the sampling time (within site comparisons). The beaches studied were Bellavista in Chile and Arroyo Hondo in California. ir = interacting rock revetment, nir = non-interacting rock revetment, iw = interacting wall, niw = non-interacting wall.

and the rock revetment at Faria. Along the seawall, the abundance of *Emerita analoga*, was lower along the interacting shoreline compared with the non-interacting shoreline (Fig. 9), however those differences were not significant ($p > 0.05$, $H = 1.16$, effect size = 6). On the other hand, abundance of this highly mobile swash zone species was significantly lower ($p < 0.05$), along the interacting shoreline of the rock revetment compared with the non-interacting shoreline ($H = 10.7$, effect size 56) (Fig. 9). Similar to that observed for talitrid amphipods, along shore variability of the log $n + 1$ transformed abundance of hippid crabs on this armored shoreline varied significantly ($p < 0.05$) with width of the habitat zone (the distance from armoring to the upper swash limit) for the rock revetment ($r^2 = 0.476$). However, this was not the case along the seawall section of this shoreline where there was a weak negative trend of log $n + 1$ transformed abundance with habitat zone width ($r^2 = 0.231$) (Fig. 9).

4. Discussion

Our results showed that the presence of coastal armoring was associated with significant reductions in the abundance, and even absence of some of the dominant taxa of intertidal macroinvertebrates of sandy beaches of coasts of both south-central Chile and California. Overall, our findings that effect sizes increased from the low to the high intertidal zones supported the hypothesis that the ecological impact of coastal armoring on macroinvertebrate abundance and distribution scales with intertidal zone (Fig. 1). Our finding of increasing ecological impacts of seawalls and revetments with lower elevation on the beach profile follows the physical impacts found or projected in earlier studies (Weggel, 1988; Weigel, 2002a, 2002b, 2002c) (cf. Fig. 2). Our findings for open coast beaches agree with recent ecological results from sheltered shorelines (e.g. Lee et al., 2018; Toft et al., 2014). For example,

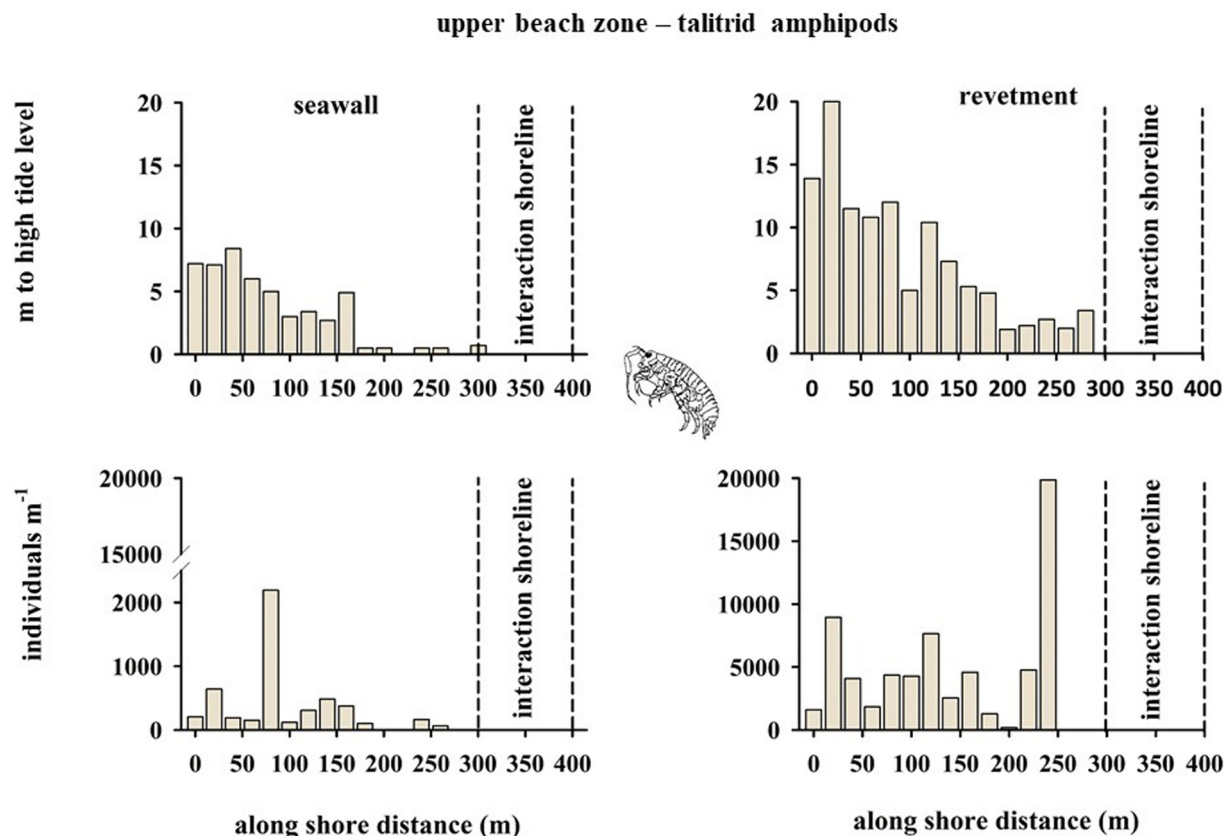


Fig. 8. Plot showing the distance from the armoring structure to high tide level and the abundance of talitrid amphipods (*Megalorchestia* spp.) along sections of shoreline armored with a seawall and a rock revetment at Faría (California). The amount of interaction of waves and swashes with the armoring structure varied along the shoreline at the time of the survey. The sections of armored shoreline that were interacting with waves and swashes are located between the dashed vertical lines on the plot.

responses of upper shore macroinvertebrates to armoring removal in sedimentary intertidal habitats in Puget Sound, WA, USA, were more noticeable than for fauna occupying low intertidal levels, (Lee et al., 2018).

Although we used a discrete set of species as indicators for our comparisons, the relative effects of armoring on intertidal zones described here can be extended to include a diversity of invertebrate taxa and wildlife. For example, the main macroinvertebrate components of the upper zone that were mostly highly impacted by armoring include the talitrid amphipods (*Orchestoidea*, *Megalorchestia* and *Talitrus*) we tested here, as well as oniscid isopods (*Tylos*, *Alloniscus*), intertidal beetles (*Phalerisidia*, *Thinopinus*, *Cafius*), other intertidal insects and ocpodid crabs (*Ocypode*) (Dahl, 1952; Trevallion et al., 1970; McLachlan and Jaramillo, 1995; McLachlan and Defeo, 2017). This upper zone is also nesting habitat for several species of sea turtles (Fujisaki and Lamont, 2016; Witherington et al., 2011a, 2011b) and fish, such as the California grunion (Martin et al., 2011, 2019). The mid intertidal zone is characterized by cirolanid isopods including the two species we studied here (*Excirolana*, *Cirolana* and *Eurydice*) and spionid and ophelid polychaetes (*Scolecopsis* and *Euzonus*, respectively). In the low intertidal, hippid crabs (*Emerita*, *Hippa*), haustoriid and phoxocephalid amphipods (*Haustorius* and *Paraphoxus*, respectively), mysids (*Gastrosaccus*), idoteid isopods (*Macrochiridothea* and *Chaetilia*), nephtyid and glycerid polychaetes (*Nephtys* and *Glycera*, respectively) and bivalves (*Mesodesma* and *Donax*), are typically found (Dahl, 1952; Trevallion et al., 1970; McLachlan and Jaramillo, 1995; McLachlan and Defeo, 2017). We expect that the ecological effects of armoring on the intertidal fauna of beaches around the world would rank similarly to that described here. Our results thus provide a foundation for the development of important global generalities concerning the ecological impacts of coastal armoring on these threatened dynamic coastal ecosystems.

The results of our comparisons of intertidal taxa along gradients of seawall and revetment position on the beach profile, as indicated by interactions with waves and tides, illustrated that as the elevation of an armoring structure decreased, the abundance of even the highly mobile swash zone-adapted hippid crabs was significantly affected (cf. Figs. 2 and 9). These results support the prediction that the relative position of an armoring structure on the beach profile determines the number of intertidal zones it influences and the resulting ecological impacts for sandy beach ecosystems. Our findings also support the general projections and results of increasing armoring impacts with increasing hydrodynamic energy for soft sediment coastlines by Dugan et al. (2017).

It is noteworthy that our current results have been indirectly corroborated by one of the ecological responses to the land level changes that originated during the 2010 Maule earthquake, with a moment magnitude 9.5 M_w along the coast of south-central Chile. Coseismic uplift from the earthquake widened beaches and restored the upper and mid shore intertidal habitat zones that had been previously lost to effects of coastal armoring (Fig. 10) (Jaramillo et al., 2012). A couple of months after the earthquake, those restored intertidal habitats were colonized by mobile crustaceans characteristic of the upper and mid shore faunal zones of sandy beaches (Fig. 10) (Rodil et al., 2016). A similar response was found in sedimentary intertidal habitats in Puget Sound, WA, USA (Lee et al., 2018): less than a year after armoring removal (i.e. habitat restoration), positive responses of abundance and species richness of macroinvertebrates were observed.

Our finding also implies that as sea level rises and existing armoring structures are effectively shifted to lower elevations on the beach profile, a corresponding increase in their ecological impacts, including the number of intertidal zones affected, can be projected. Moreover, that situation might be exacerbated along coasts that are periodically affected by land subsidence as a result of subduction earthquakes (see e.g.

lower beach zone – hippid crabs

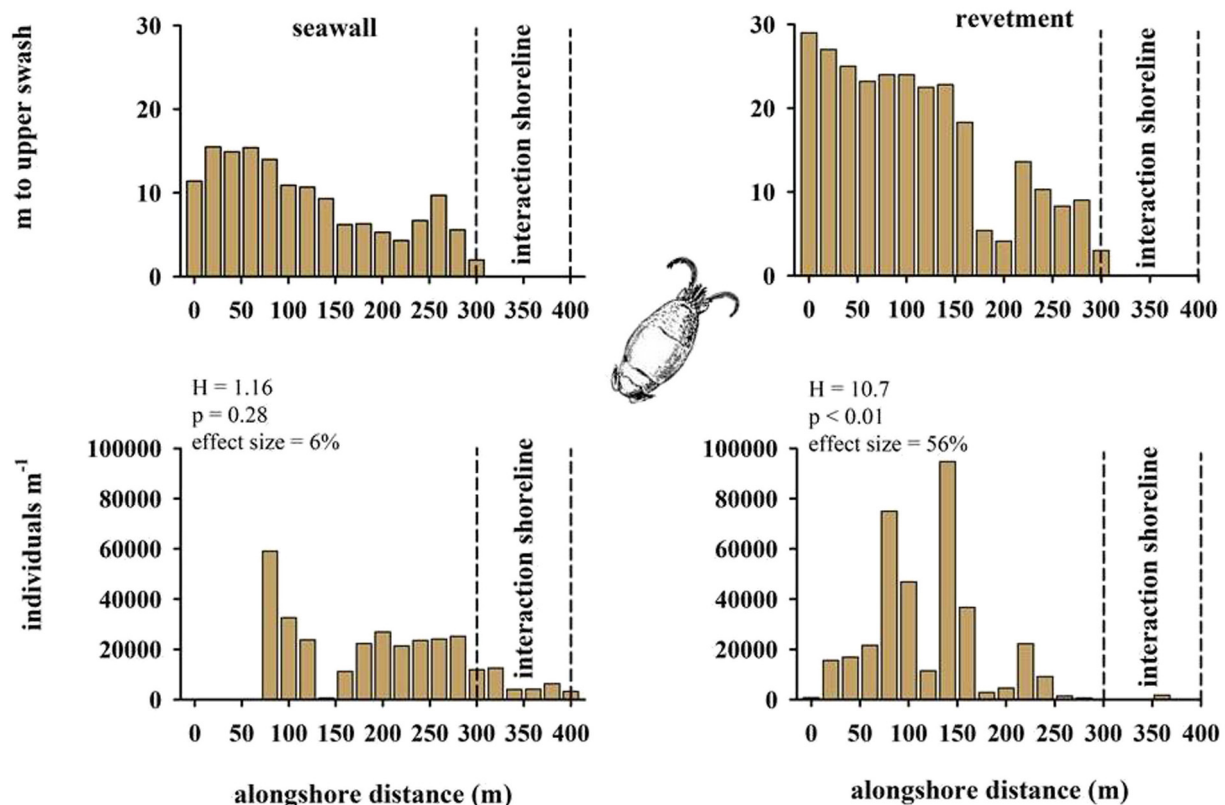


Fig. 9. Plot showing the distance from the armoring structure to upper swash level and the abundance of hippid crabs (*Emerita analoga*) along sections of shoreline armored with a seawall and a revetment at Faría (California). The amount of interaction of waves and swashes with the armoring structure varied along the shoreline at the time of the survey. The sections of armored shoreline that were interacting with waves and swashes are located between the dashed vertical lines on the plot.

Jaramillo et al., 2012, 2017) which results in a reduction of the elevation of armoring structures on the beach profile, their increased exposure to the action of waves and of tides and the consequent loss of intertidal habitat and fauna. Our results support a conceptual framework that can provide information needed to project ecological impacts of coastal armoring and to support management and conservation planning for sandy beach ecosystems worldwide. In an era of rising seas (Vitousek et al., 2017) and intensification of extreme weather variability (Smith, 2011; Sobel et al., 2016), this framework can provide new insights on the relative ecological impacts of different approaches – such as coastal armoring – to address coastal erosion and hazards.

5. Conclusions

Our study has revealed a consistent pattern for open coast sandy beaches: coastal armoring strongly affects the diversity and abundance of intertidal macroinvertebrates. The presence of seawalls and rock revetments in the upper intertidal zone, significantly decreases the abundances of upper and mid intertidal zone species (talitrid amphipods and some isopod species) (cf. Fig. 1) and can eliminate these important taxa from armored beaches. Although the abundance of macroinvertebrate species typical of lower intertidal zones (hippid crabs and a cirrolanid isopod) were, as predicted, generally less affected by coastal armoring, where armoring structures were located low on the beach profile, even the low intertidal hippid crab was negatively affected. Our results support the hypothesis that the proximity of an armoring structures to sea level determines the number of intertidal zones it impacts (cf. Fig. 2). Overall, our conceptual framework and results on the ecological

impacts of armoring are likely to be broadly applicable to open coast sandy beach ecosystems in other regions and latitudes.

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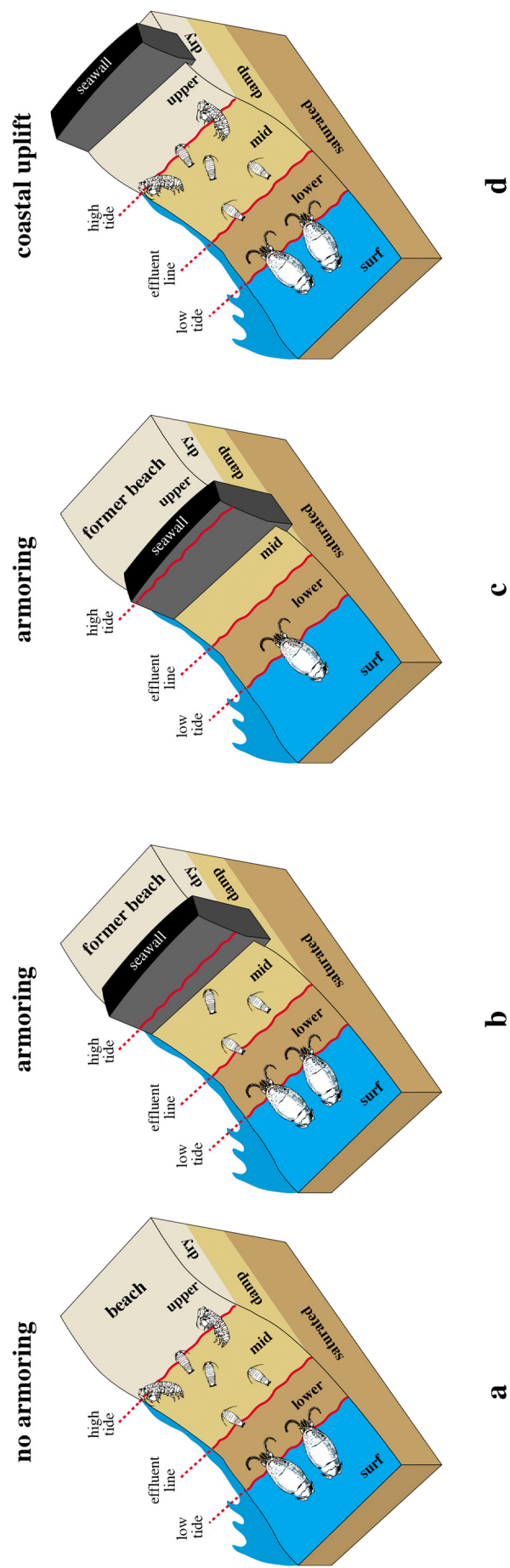


Fig. 10. Schematic representation of the interaction between coastal armoring and the coastal uplift or land level change resulting from the 2010 Maule earthquake along the coast of south-central Chile. a) a sandy beach without armoring that has the full complement of intertidal zones and species typical of this coast, b) a sandy beach with an armoring structure located high in the intertidal that affects the upper beach zone, c) a beach with an armoring structure located lower in the intertidal profile – as compared with b – that affects the fauna of the mid and upper beach zones, d) an armored beach showing the same intertidal zones and species as found on an unarmored beach (a) due to habitat recovery resulting from that land level change.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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